

The Diffuse Galactic Gamma Ray Emission

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ABSTRACT

The EGRET detector will provide a much more detailed view of the diffuse galactic gamma ray intensity in terms of higher resolution, greater statistical significance, and broader energy range than earlier missions. These observations will furnish insight into a number of very important questions related to the dynamics and structure of the Galaxy. A diffuse emission model is being developed that incorporates the latest information on matter distribution and source functions. In addition, it is tailored to the EGRET instrument response functions. The analysis code of the model maintains flexibility to accommodate the quality of the data that is anticipated. The discussion here focuses on the issues of the distributions of matter, cosmic rays, and radiation fields, and on the important source functions that enter into the model calculation of diffuse emission. A subsequent paper in this conference reports the details of the analysis and preliminary results.

INTRODUCTION

When the sky is viewed in the high energy domain of gamma rays, the most prominent feature that is observed is a narrow band of emission that extends along the entire galactic plane. The intensity within the band has a broad maximum in a region of about 100 degrees in longitude, located about the galactic center. This emission feature was first detected by OSO-3 (Kraushaar et al., 1972), and it was been observed extensively in the subsequent SAS-2 (Fichtel et al., 1975; Hartman et al., 1979) and COS-B (Mayer-Hasselwander et al., 1980 and 1982) missions. Figure 1 shows the results from COS-B. The longitude distribution, shows a remarkable amount of structure, and in latitude it falls rapidly with a width of only a few degrees. Bignami and Fichtel (1974) and Bignami et al. (1975) using the SAS-2 data observed that the intensity was enhanced along longitudes associated with tangent directions of spiral arm features. Subsequent analysis of both the SAS-2 (Fichtel et

al., 1975 and Hartman et al., 1979) and COS-B (Mayer-Hasselwanger et al., 1982) data confirmed this correlation.

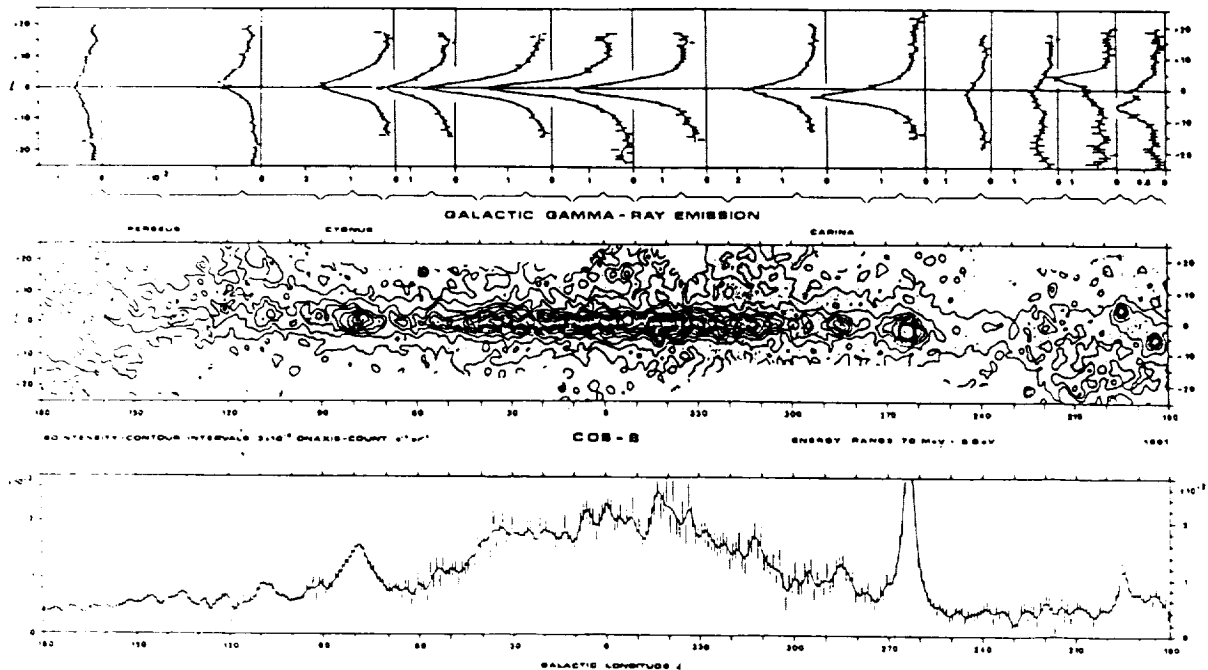


Figure 1. Galactic gamma ray emission observed by COS-B. In the latitude profile, the brackets indicate the interval of longitude used. The contour amp and the longitude profile show on-axis counts per steradian. Contours are in steps of 3×10^{-3} per steradian. For the longitude profile, data are averaged over ± 5 degrees. This figure is from Mayer-Hasselwanger et al. (1982).

Evidence based on the spatial correlation of intensity with galactic matter distribution, and on the energy spectrum suggests that the emission arises from cosmic ray interactions between interstellar matter and low energy photons. A distribution of point sources that cannot be resolved by the angular response of these two instruments could contribute to the total emission. The uniformity of the energy distribution, and the ability of the diffuse emission processes to explain the gamma ray luminosity and its distribution, however, argues against unresolved sources being a major contributor.

The concept that cosmic ray-matter interactions are the source of the diffuse emission has led to a several modeling efforts with aim of comparing the observed distribution with the calculated one. (See, for example, Bignami and Fichtel, 1974; Paul, Casse, and Cesarsky, 1974 and 1976; Schickeiser and Thielheim, 1974; Puget, Stecker, and Bredekamp, 1976; Hartman et al., 1979; Kniffen and Fichtel, 1981; Fichtel and Kniffen, 1984;

Blat et al., 1985; Harding and Stecker, 1985; Bloemen et al., 1986; and Strong et al., 1988 and recent surveys by Fichtel, 1989 and Bloemen, 1989.) The models generally incorporate information on the galactic matter distribution obtained from radio surveys. In addition, the optical and infrared photon fields are assumed, based on stellar populations and infrared surveys. No evidence is available for the cosmic ray distribution, and it is one of the goals of these calculations to identify constraints on the distribution based on the observed gamma ray emission. Three distinct approaches have been followed. The first assumes a distribution of cosmic rays that is coupled in some degree to the matter by magnetic fields. The distribution of gamma rays is then computed and compared to the observations. The process is iterated with different assumptions on the degree and scale size of the coupling until the best fit to the data is obtained. This is the approach taken by the SAS-2 group (e.g., Fichtel and Kniffen, 1984). Another approach employed by Harding and Stecker (1985) uses an unfolding technique to infer the galactic radial dependence of cosmic rays. The third approach used by the COS-B collaboration (e.g., Bloemen et al., 1986) uses a maximum likelihood analysis to determine the cosmic ray intensity in a series of galactocentric bins.

This paper provides a general discussion of the matter, cosmic ray, and radiation field distributions and the source functions for interactions between cosmic rays, matter, and photons. These are the essential ingredients of a model that is under development that will serve in interpreting the EGRET data. More specific details of the calculation and early results from the model are given by Sreekumar (1990) (this conference).

DIFFUSE EMISSION MODEL FOR EGRET ANALYSIS

During the first 15 months of the GRO mission, EGRET will conduct an all-sky survey. The galactic plane region will be one of the priority observations during this time. The increase in sensitivity of EGRET as compared to SAS-2 and COS-B by over an order of magnitude, together with the improved angular and energy resolution, and the significantly greater energy range will greatly improve knowledge of the gamma ray intensity and distribution in both longitude and latitude.

In anticipation of these results, a new model is being developed as a collaboration between members of the EGRET team and radio astronomers at the Center for Astrophysics. Preliminary results of this work have been reported previously (Bertsch et al., 1990a,b). The new model incorporates the most up-to-date information on the matter distribution from radio survey data. Recent work on interstellar electron energy spectrum is included, as is a refined production spectrum from nucleon interactions. To maintain the greatest flexibility in using trial cosmic ray distributions, the first of the three approaches discussed above is followed, namely, to assume a

distribution for cosmic rays, calculate the diffuse emission, convolve the line of sight intensity with the point spread function and energy resolution of EGRET to produce a distribution comparable with the one the instrument produces.

The goals of the study are to provide insight into the cosmic ray distribution, and the degree to which it couples to the matter. Further, since cosmic rays interact equally well with atomic and molecular hydrogen, the model is expected to help to understand the normalization between the atomic and molecular components. At the present time, molecular hydrogen is indirectly inferred from observations of CO. As will be seen in later sections, the source functions of electrons and nuclei have a very different energy dependence, and consequently, the model can be used with observations of the gamma ray energy spectrum as a function of longitude and latitude to study the ratio of cosmic ray electrons and nuclei as a function of location in the galaxy. Also, the observed latitude dependence of the gamma rays might be used to infer differences between the scale height of matter and the low energy photon radiation fields using the model. Finally, the model will provide a means of estimating background in searching for sources and evaluating their statistical significance.

GALACTIC MATTER DISTRIBUTION

Galactic matter is present in a wide range of forms that include ions, atoms, molecules, and dust grains. The most abundant constituent is atomic and molecular hydrogen, together accounting for 90% of the total, and helium making up nearly all of the rest. The matter is known to be distributed in a thin disk of about 18 Kpc in radius. Atomic hydrogen has a scale height of about 120 pc, while molecular hydrogen is only about 50 pc. Molecular hydrogen appears to dominate in the inner Galaxy, and in the outer Galaxy, atomic hydrogen is more abundant. In addition, the matter distribution is non-uniform with concentrations in spiral arms and molecular clouds. The average density in the plane is about 1 cm^{-3} .

Observations from several surveys were joined into a uniform grid to serve as the basis of the current model. For the atomic hydrogen in the latitude interval from +10 to -10 degrees, the surveys of Weaver and Williams (1973), Kerr et al. (1986), and Burton and Liszt (1983) and Burton (1985) are used. The grid resolution is 0.5 degree in longitude and 0.25 degree in latitude, except for the galactic center region (longitude -10 to 10 degrees) where a one degree spacing in latitude and longitude is used. The molecular hydrogen map is based on several radio surveys of the 2.6 mm line of ^{12}CO assembled by Dame et al. (1987). It covers the entire plane in 0.5 degree bins, typically between -10 and 10 degrees of latitude, but with larger excursions in certain locations. The conversion from the CO antenna temperature to molecular hydrogen density is not well established. Because of the differences in the spatial

distribution of atomic and molecular hydrogen, it is possible that observations together with the model predictions can determine the normalization. This is another one of the goals of this calculation. Presently, the analysis is using the value $2.3 \times 10^{20} \text{ mol cm}^{-2} (\text{K km s}^{-1})$.

The radio maps represent line of sight column densities of matter as a function of recessional velocity and position. The galactic rotation curve of Burton and Gordon (1978) is used to convert from radial velocity to radial distance from the center of the galaxy. For radii less than that of the sun (taken to be 10 Kpc), the line-of-sight intersects a circle at a given radius at two points, and at both points, the recessional velocity is the same. Hence, there is a two-fold ambiguity in the conversion to radius for $R < 10 \text{ Kpc}$. This can occur in the first and fourth quadrants only. When axially symmetric cosmic ray distributions are used, or when the intensity is proportional to matter, the ambiguity is of no consequence. Currently, there is no clear method for resolving the ambiguity. Some guidance can be obtained from mapping giant molecular clouds whose distance can be estimated using related HII regions and OB associations. At present, only about 18% of the molecular hydrogen could be accounted for in this manner in a study made for the first galactic quadrant (Dame et al., 1987). Until there is a better grasp on this problem, it will be necessary to assume in the model some distribution between the two points of ambiguity. An equal division is being used at this time.

COSMIC RAY DISTRIBUTION AND INTENSITY

Protons constitute 90% of the nuclear component of cosmic rays while helium makes up nearly all of the rest. The electron component is only about 1% as numerous as nucleons. Evidence based on the cosmic ray lifetime of somewhat over 10^7 years deduced from the composition of unstable secondaries such as Be^7 , together with the average path length of about 4 g cm^{-2} indicated by the abundance of light isotopes, suggest that the average density traversed by cosmic rays is about 0.1 g cm^{-2} which is only about 10% of the matter density in the plane. Consequently, they must spend most of their time outside the plane. In addition, the non-thermal radio continuum, presumably from electron synchrotron emission in galactic magnetic fields suggests a scale height of 750 pc from the central plane. The assumption that the magnetic field and electrons and protons all have about the same dependence on distance from the plane, yields a estimate of 1 Kpc for the scale height. This is consistent with the mean matter traversed.

As mentioned above, the distribution of cosmic rays in the galactic plane is not known from observations. Theoretical arguments, however, can be made to suggest that the cosmic rays are coupled at some scale size to the matter through the magnetic fields. Cosmic rays are thought to be primarily of galactic origin since their mean lifetime is only about 10^7 years,

and moreover if they were not, inverse Compton interactions of electrons with the blackbody background would seriously degrade the electron spectrum in the lifetime of the Galaxy. The gravitational attraction of matter in the plane is the only force that constrains the expansive pressure of the cosmic rays and magnetic field. Locally, the energy density of cosmic rays, magnetic field, and the motion of matter are all about 1 eV cm^{-3} . This energy density is estimated to be near the maximum expansive pressure that can be contained by the gravitational attraction. In other words, a state of near equilibrium between cosmic rays, magnetic fields, and matter exists. If it is assumed that the conditions in the solar vicinity are typical of the Galaxy as a whole, then the cosmic ray density throughout the Galaxy must be nearly as large as can be contained by the matter, and the cosmic rays are constrained or tied to the matter by closed magnetic field lines.

Based on these arguments, it is expected that the cosmic ray density is correlated with matter density for size scales greater than some threshold value. The size scale, and coupling strength remain to be determined by observations. The coupling scale on the order of spiral arm widths, 0.1 to 1.0 Kpc, have been suggested in earlier models, especially those based on the SAS-2 data (Fichtel and Kniffen, 1984).

GALACTIC PHOTON DISTRIBUTION

Inverse Compton collisions between cosmic ray electrons and low energy photons provides a mechanism for diffuse gamma ray production. Three different radiation fields have been found to be important: blackbody, starlight in the wavelength region near the visible, and the infrared. The spatial distribution of blackbody is of course uniform.

Regarding the interstellar radiation field, Kniffen and Fichtel (1981) assume the emissivity follows the stellar disc population distribution of Bahcall and Soneira (1980), and they normalize the distribution to the local value. Bloemen (1985) used a model developed by Mathis et al. (1983) which gives somewhat lower values. More recently, Chi et al. (1989) develop an interstellar radiation field model also based on Mathis et al. (1983) which is significantly more intense, and has a higher scale height from the plane.

The infrared distribution used by Kniffen and Fichtel (1981) is based on an unfolding of a galactic plane survey by Boisse et al. (1981). The Bloemen (1985) model used results of Mathis et al. (1983) also in the infrared and obtained a significantly lower intensity. Chi et al. (1989) arrive at values similar to Bloemen.

In summary, there is considerable divergence in the intensity and distribution of the interstellar and infrared photon fields. Fortunately, the contribution from inverse Compton scattering is less significant (~10% in the plane) than for the cosmic ray matter interactions. However, since cosmic rays and

perhaps the photon fields have a higher scale height than matter, the Compton process is expected to become more important as distance from the plane increases. At the present stage of development, the model under discussion here does not include the contributions from inverse Compton. After further study of the problem, this source will also be incorporated.

GALACTIC DIFFUSE EMISSION PROCESS

The previous sections have discussed the basic ingredients for the interactions that produce gamma rays in the interstellar medium. Among the interactions that can occur, the three that are dominant, and will eventually be a part of the model, include nuclear interactions between cosmic rays and matter, bremsstrahlung collisions between electrons and matter, and inverse Compton scattering between electrons and low energy photons. The model does not include synchrotron emission from electrons in the magnetic field as this is estimated to have a negligible contribution. In addition, line emission from dust and grains that are excited by cosmic ray collisions and contributions from unresolved point sources are not intended to be a part of the model.

Gamma rays are produced in collisions of cosmic rays and matter through the production of secondary pions which in turn decay. Neutral pions decay directly usually into two gamma rays, and positive pions decay into positrons that in turn may annihilate near rest to produce a 0.511 Mev line. Stecker (1970,1979) developed a model which was subsequently refined by Dermer (1986) that describes the production of gamma rays by cosmic rays through neutral pion decay. The differential energy spectrum of the production function per atom of interstellar material is shown in figure 2. Notice that the spectrum has a maximum at the half the rest mass of the neutral pion, 68 MeV. This function has been parameterized for incorporation into the model as follows:

For $10 \text{ MeV} < E < 1.5 \text{ GeV}$,

$$Q_n(E) = a \log[-25.58 - 2.36(\log E) - 1.04(\log E)^2] \text{ (cm}^3 \text{ s GeV)}^{-1}$$

For $1.5 \text{ GeV} < E < 7 \text{ GeV}$,

$$Q_n(E) = 3.2 \times 10^{-27} E^{-1.5} \text{ (cm}^3 \text{ s GeV)}^{-1}$$

For $7 \text{ GeV} < E < 40 \text{ GeV}$

$$Q_n(E) = 4.6 \times 10^{-26} E^{-2.86} \text{ (cm}^3 \text{ s GeV)}^{-1}.$$

Electrons also interact with matter to produce gamma rays by the bremsstrahlung process. If the electron energy spectrum is a power law, the gamma rays distribution will have the same power law dependence on energy. The interaction is well understood, but considerable uncertainty exists in the electron

spectrum for energies below about 5 GeV due to the influence of solar modulation. Fichtel, Ozel, and Stone (1990) estimated the electron spectrum based on gamma ray observations at energies below the maximum in the nucleon source function (See figure 2.). In this regime, bremsstrahlung dominates. The spectrum they derive was found to tie smoothly to the observed electron spectrum above 10 GeV where modulation is not important. The spectrum from their analysis is shown plotted in figure 3. This spectrum together with the bremsstrahlung cross section results in bremsstrahlung source functions:

For $10 \text{ MeV} < E < 5 \text{ GeV}$,

$$Q_e(E) = 4.4 \times 10^{-27} E^{-2.35} \text{ (cm}^3 \text{ s GeV)}^{-1}$$

For $5 \text{ GeV} < E < 40 \text{ GeV}$,

$$Q_e(E) = 2.1 \times 10^{-26} E^{-3.3} \text{ (cm}^3 \text{ s GeV)}^{-1}$$

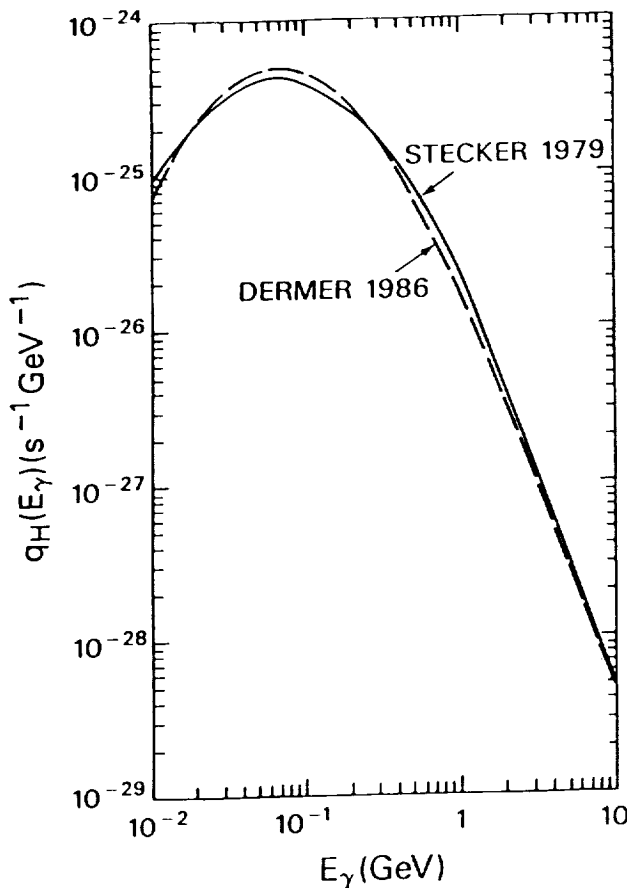


Figure 2. Gamma ray production from cosmic ray nucleon interactions. From Stecker (1988).

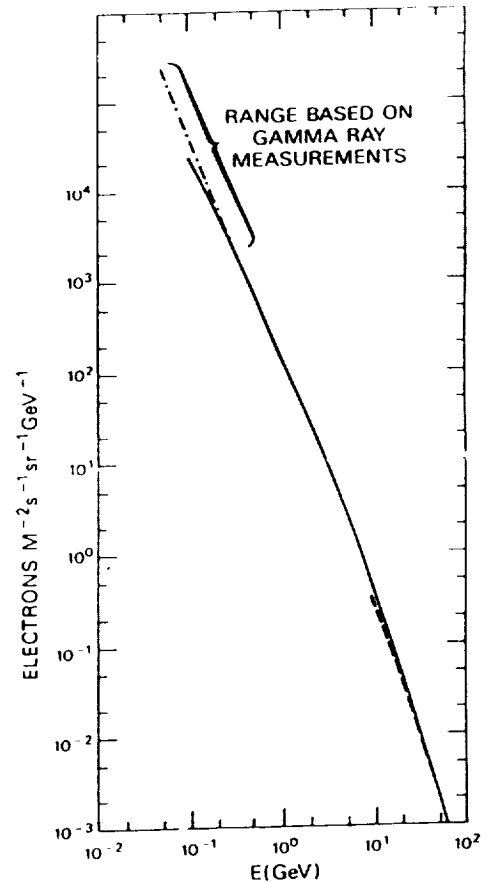


Figure 3. Interstellar electron differential energy spectrum. From Fichtel, Ozel, and Stone (1990).

Gamma rays produced from the inverse Compton process have an energy that scales from the electron and photon energy according to

$$E_g = (E_e/m_e c^2)^2 \times E_{ph}$$

where E_g , E_e , and E_{ph} are the gamma ray, electron, and photon energies, and $m_e c^2$ is the electron rest energy. Consequently, very high energy electrons are required to produce gamma rays. For example, a 100 MeV gamma produced by this mechanism requires an electron of energy from 7 to 200 GeV, depending on the target photon energy. If the electron spectrum has a power law dependence with index $-a$, then the source function for the inverse Compton process has an energy power law with index $-(a+1)/2$. As mentioned above, the inverse Compton process has not yet been incorporated in the model since the best choice of the photon radiation fields has been made at this stage.

Figure 4, taken from Fichtel and Kniffen (1984) shows the predicted gamma ray spectrum in the galactic plane near the center, together with low energy gamma ray observations. The relative contributions of the three sources just described are identified. Below about 100 MeV, the bremsstrahlung component is dominant, while above 100 MeV, the nuclear contribution is the strongest. Note the relatively minor role of the inverse Compton component. The spectrum shows a clear break in the transition region. Observations such as these, in the detail that will be available from EGRET, will provide

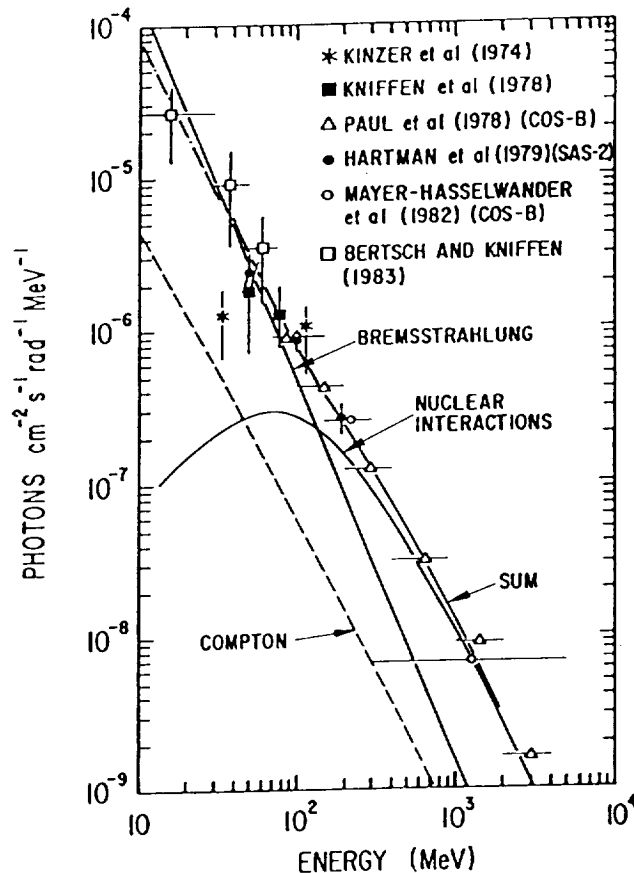


Figure 4. Energy spectrum of galactic radiation in a region near the galactic center. The curves are from a calculation by Fichtel and Kniffen (1984). The contribution from the different sources and the total are labeled. The figure is taken from Fichtel and Kniffen (1984) where references to the data are given.

information on the relative contributions of electrons and cosmic rays as a function of galactic longitude. When observations are made at latitudes off the plane, the Compton contribution may become relatively more significant, and such observations may lead to information on the photon field intensities and scale height.

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DISCUSSION

Volker Schonfelder:

The topic of diffuse galactic gamma-ray emission is an ideal example, where the combination of results from more than one GRO telescope will give more information than the result from one instrument by itself. Adding the results on the diffuse emission from COMPTEL to those of EGRET will lead to a clearer separation of the various diffuse gamma-ray components like π^0 -decay, bremsstrahlung and the inverse Compton component.

David Bertsch:

I am glad you mentioned that point. I had intended to point that out.

